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Late Eocene microkrystites and microtektites at Maud Rise (Ocean Drilling Project Hole 689B; Southern Ocean) suggest a global extension of the approximately 35.5 Ma Pacific impact ejecta strewn field

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Abstract–Late Eocene microtektites and microkrystites recovered from Ocean Drilling Project Hole 689B at Maud Rise (Southern Ocean) are stratigraphically and geochemically compared to spherules from the North American and Pacific strewn fields, and to devitrified spherules from the Eocene–Oligocene global stratotype section and point section in Massignano, Italy.

The ODP 689B microkrystites compare well to the Pacific strewn field microkrystites, which suggests that the geographic extent of the Pacific strewn field was much larger than previously documented.

The elemental composition of microtektites of ODP Hole 689B is comparable to tektites of the North American strewn field. Their $^{87}Sr/^{86}Sr$ ratio, however, is different. We tentatively interpret this to reflect geochemical heterogeneity within the North American strewn field but can not exclude the option that the chemical discrepancies result from the existence of a third late Eocene impact site.

INTRODUCTION

Late Eocene Strewn Fields

Late Eocene tektites, the glassy ejecta from extraterrestrial impacts, are known to occur at a number of locations on the North American continent. These tektites (also known as bediasites or georgiaites) were first recognized in the late 1930s and have since been reported from many sites on the continent (see Koeberl, 1989, and Barnes, 1990, for a historical overview). Microtektites (tektites <1 mm in diameter) were found in drill cores from the Caribbean and the Gulf of Mexico, apparently belonging to the same North American tektite strewn field, based on their geographic and stratigraphic occurrence, fission track and $^{40}Ar/^{39}Ar$ age, and chemical composition (Glass *et al.*, 1985; and references therein).

John and Glass (1974) reported clinopyroxene-bearing spherules, which they initially interpreted to be associated with the North American strewn field. Glass and Burns (1988) termed such clinopyroxene-bearing spherules microkrystites. Similar microkrystites were found at the Cretaceous–Tertiary boundary (Smit *et al.*, 1992) and in ejecta from a late Pliocene impact (Margolis et al., 1991)

A late Eocene Ir anomaly was found at Deep Sea Drilling Project (DSDP) site 149 (Alvarez *et al.*, 1982), and in core RC9-58 (Ganapathy, 1982) in the Caribbean Sea. It was suggested to be associated with the North American microtektite strewn field, although the Ir peak in core RC9-58 is located below the peak occurrence of the microtektites. Also in the late Eocene section in Barbados, an Ir anomaly occurs ~27 cm below the microtektite layer (Sanfilippo *et al.*, 1985). Detailed reanalysis of core RC9-58 (Glass and Ganapathy, 1982) showed that, although bioturbational mixing disturbed the section, the main peak of microkrystites coincides with the Ir anomaly, ~25 cm below the peak microtektite abundance. These data indicate the presence of two separate impact events: One with an Ir anomaly, abundant microkrystites, and some microtektites; followed by a 10–20 ka later impact, producing tektites and microtektites only (Glass *et al.*, 1985). In accordance with their geographical extent, they are referred to as the Pacific strewn field and the North American strewn field, respectively. Tektites from the North American strewn field seem largely restricted to an area around the Gulf of Mexico and the western North Atlantic, whereas the Pacific strewn field extends from the Caribbean across the equatorial Pacific to DSDP Site 216 in the Indian Ocean (Fig. 1). At a number of sites, the Pacific strewn field microkrystite horizon is associated with an Ir anomaly (Glass *et al.*, 1985).

Keller *et al.* (1983) reported at least four stratigraphically different microtektite horizons in the upper Eocene, but two of those horizons could not be confirmed (Glass *et al.*, 1985). Hazel (1989) distinguished even six different microspherule (microkrystite and

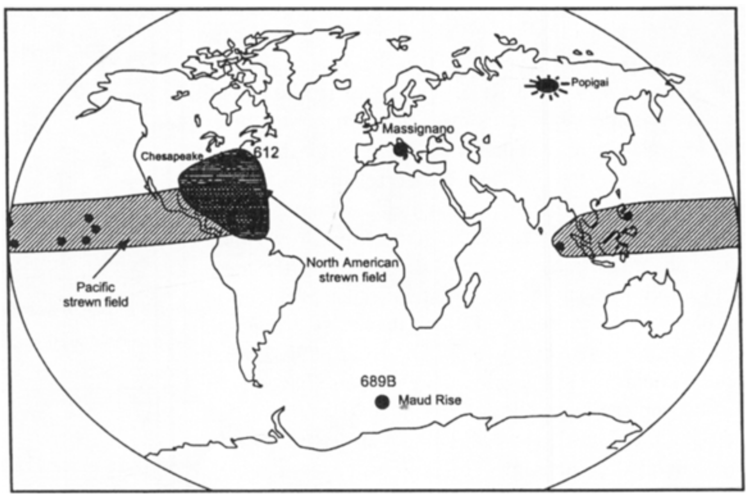

FIG. 1. World map showing occurrences of late Eocene impact ejecta. Longitudinally elongated hatched area indicates the extension of the Pacific strewn field, not counting Massignano and Maud Rise. Black dots are the actual ODP or DSDP sites where ejecta have been found. The smaller North American strewn field is indicated by the shaded area covering the North American east coast, Gulf of Mexico, and Caribbean Sea. Suggested source craters on the North American east coast (Chesapeake Bay), and in Siberia (Popigai) are also indicated. 612 and 689B refer to DSDP Site 612 and ODP Hole 689B (Maud Rise), respectively.

microtektite) layers in the upper Eocene, based on a graphic correlation technique of biostratigraphic datum levels. However, Glass (1990) and Wei (1994) showed that these datum levels can be diachronous and that the present data do not require more than two strewn fields.

Biotic Changes Across the Ejecta Layers

The Pacific strewn field horizon is associated with the extinction or strong decrease in abundance of at least five biostratigraphically important radiolarian species (*Thyrsocyrtis bromia, T. triacantha, T. finalis, T. tetracantha,* and *Calocyclas turris*) (Maurrasse and Glass, 1976; Sanfilippo *et al.*, 1985). In fact, the extinction of these five species is often used to locate the position of the North American microtektite and the microkrystite horizons in deep sea cores (Glass and Zwart, 1977; Glass *et al.*, 1985). No extinctions of foraminifera have been reported at the ejecta layers, although changes in the foraminiferal assemblages do occur (Keller, 1986).

Ejecta from Massignano and Maud Rise

Montanari *et al.* (1993) found a late Eocene Ir anomaly at two other sites, well outside the then known geographical extension of the Pacific strewn field. One of these sites is the Global Stratotype Section and Point (GSSP) for the Eocene–Oligocene boundary, near Massignano in Italy; the other is ODP Site 689 at Maud Rise, in the Southern Ocean. High-resolution Ir scanning yielded a well-defined Ir anomaly in both sections, with maxima of 0.2 and 0.16 ppb, respectively. The Ir peak abundance is at meter level 5.61 of the Massignano standard E/O stratotype section, and at 128.70 m below the seafloor in ODP Hole 689B (Fig. 2).

Clymer *et al.* (1996) and Langenhorst (1996) found shocked quartz grains, with well-defined PDFs (planar deformation features) exclusively at the horizon with the Ir anomaly in the Massignano section. Subsequently, Pierrard *et al.* (1998) found, in the same layer, numerous flat disks, about 0.2–0.5 mm in diameter, containing abundant Ni-rich spinel crystals, which are presumably diagenetically devitrified and flattened spherules.

We report the finding of late Eocene microtektites and microkrystites at level 128.70 m below sea floor in ODP Hole 689B (Maud Rise) and compare them with late Eocene impact spherules from Massignano and other sites to investigate whether they belong to the same impact ejecta layers. A positive correlation of one or both of the known ejecta strewn fields with the Maud Rise spherules would extend the size of the strewn field to global proportions, whereas distinctive differences would imply that another strewn field must be added to the ones already reported for this time interval. Following the discovery of the ODP Hole 689B impact ejecta (Vonhof, 1998), two more papers have been published on the microtektites and microkrystites of this core (Glass and Koeberl 1998; Glass and Koeberl, 1999) with generally comparable conclusions concerning the source of these spherules to those outlined in the current paper.

STRATIGRAPHIC FRAMEWORK

Magnetostratigraphy

Magnetostratigraphic records exist for both Massignano and Maud Rise. Some problems have arisen, however, in the interpretation of the ODP 689B record. The normal polarity interval in which the ejecta layer occurs has been interpreted as chron C15N by Spieß (1990) and alternatively as chron C16N by Stott and Kennett (1990). (See also the discussion in Montanari *et al.*, 1993.) Based on general sediment accumulation rates and biostratigraphic arguments outlined by Mead and Hodell (1995), we favour the Stott and Kennet interpretation. With this interpretation the ejecta layer would fall in chron C16N.2 for Massignano and in C16N.1 for Maud Rise. However, the short reversed interval between chron C16N.1 and C16N.2 in ODP Hole 689B is defined by a single weak intensity analysis, on a sample that is taken from a disturbed core catcher. We therefore support the suggestion of Montanari *et al.* (1993) to discard this analysis, resulting in an undivided chron C16N at Maud Rise. Also in the Massignano section, only one out of two studies reports this short reversed interval between chron C16N.1 and C16N.2 (Bice and Montanari, 1987; Lowrie and Lanci, 1994). Although Bice and Montanari (1987) define the reversed interval in two samples, and both studies also find it in the nearby Contessa section, this reversed interval appears short enough to be overlooked.

Thus comparing the modified magnetostratigraphy, leaving out the short reversed interval in chron C16N, the top of chron C16N lies in a zone between 0.9 and 2.4 m above the ejecta layer in Massignano, and in between 0.25 and 0.50 m above the ejecta layer at Maud Rise (Fig. 2). In Fig. 2, we have further indicated the maximum uncertainties of the location of each reversal in gray. This uncertainty represents the sample distance for Maud Rise, and the sample distance increased by discrepancies between both magnetostratigraphic studies for Massignano. The comparison of these adapted magnetostratigraphic records does not necessarily indicate a time gap between the ejecta layers of Massignano and Maud Rise, provided one accepts a somewhat lower accumulation rate for Maud Rise than for Massignano directly above the impact layer.

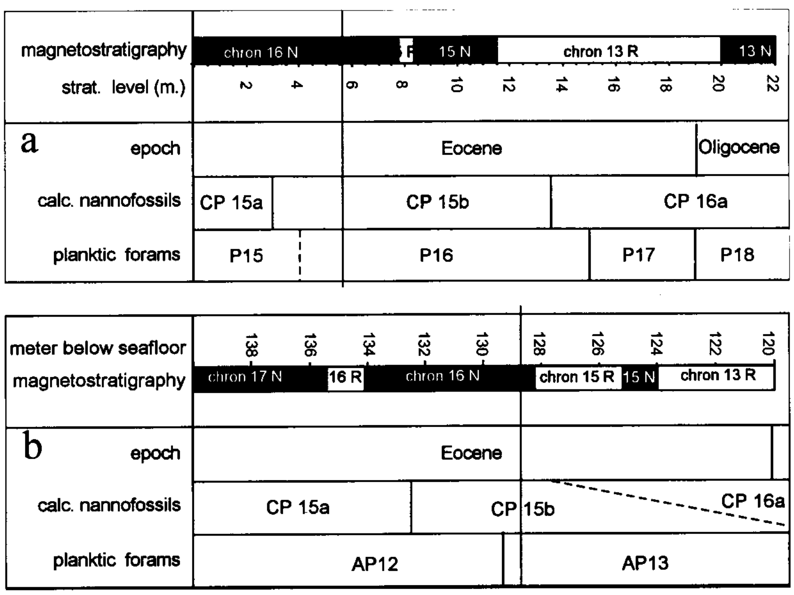

FIG. 2. Magnetostratigraphy of the Massignano section (a) and ODP Hole 689B (b). See text for a discussion of the magnetostratigraphic records. Gray areas in the magnetostratigraphic column mark the maximum uncertainty due to sample density and the compilation of different magnetostratigraphic studies. Vertical lines at 128.70 m in ODP Hole 689B and at 5.61 m in the Massignano GSSP section mark the location of the impact ejecta layer with the Ir anomaly.

Radiometric Ages

Argon-40/Argon-39 ages of 35.4 ± 0.6 and 35.5 ± 0.3 Ma were reported for tektites from the North American strewn field (Glass *et al.*, 1986; Obradovich *et al.*, 1989). For the Massignano impact ejecta layer, extrapolated radiometric ages result in 35.7 ± 0.4 Ma (Montanari *et al.*, 1993). All of these ages overlap, which supports the notion that the associated Ir anomalies record the same impact.

METHODS

Bulk carbonate ooze samples from ODP Hole 689B were disintegrated in water, sieved, and dried. Spherules were picked from the >125 μm fraction. For microprobe analyses, spherules were mounted on a glass slide and polished to obtain clean cross sections. Elemental analyses of the spherules were carried out on a JEOL JXA-8800M electron microprobe, applying a defocussed spot (10–20 μm) at 15 kV. For spinel analyses, the spot was focussed to ~1 μm.

Strontium-isotopic analyses took place according to standard analytical procedures on a Finnigan MAT 261 solid-source mass spectrometer (for a more detailed description see Vonhof, 1998). Samples were digested in a mixture of HF and HNO_3. Data are normalised to a value of 0.1194 for $^{86}Sr/^{88}Sr$ and reported compared to a $^{87}Sr/^{86}Sr$ value of 0.710244 for the NBS 987 standard.

Strontium concentration data of seven individual ODP Hole 689B microtektites (INAA, 100 h irradiation at a flux of 6×10^{13} n/cm^{2}s) were kindly donated by C. Koeberl (pers. comm., 1998).

RESULTS

Maud Rise Spherules

In ODP Hole 689B, we found well-preserved impact spherules at the 128.70 m below sea floor Ir anomaly reported by Montanari *et al.* (1993). Spherules can be divided in two types, microkrystites and microtektites, occurring in a 20 cm interval enveloping the Ir anomaly. The number of microtektites in the >125 μm fraction is low, ~3 spherules per gram dry sediment (Table 1). The largest transparent microtektites are ~600 μm (Fig. 3a). The >125 μm microkrystites (Fig. 3b) are fewer and smaller but were not counted per gram sediment.

The vertical distribution of Maud Rise spherules does not show evidence for a stratigraphic separation between microkrystites and microtektites. They resemble late Eocene spherules described by Glass *et al.* (1985). The microkrystites especially have many features in common, like the shape and size of clinopyroxene and spinel crystals, occasional olivine crystal ghosts, and the occurrence of cryptocrystalline spherules (Fig. 3b). Maud Rise microtektites are mostly colorless, which is also the case for a number of the North American microtektites (Glass *et al.*, 1985). We did not encounter inclusions of lechatelierite or coesite in the microtektites, which were reported for some of the North American tektites (Glass *et al.*, 1985; Glass and Wu, 1993).

In Fig. 4, Al_2O_3, and SiO_2 microprobe data for Maud Rise spherules are shown compared to compiled data of North American strewn field tektites taken from Glass *et al.* (1985), Ngo *et al.* (1985), Shaw and Wasserburg (1982), and Stecher *et al.* (1989). This plot shows that a distinct chemical difference exists between the Maud Rise microtektites and microkrystites, which is also evident in the MgO, Al_2O_3, CaO, and Na_2O content. This is very similar to the difference between North American strewn field (micro)tektites and Pacific strewn field microkrystites. Some Maud Rise spherules that were first identified as microtektites under the optical microscope, but chemically plotted in the microkrystite field, were reexamined under the scanning electron microscope (SEM) and found to have a cryptocrystalline structure. Despite a typical microkrystite composition (*e.g.*, high MgO), two showed no signs of crystallization and consequently remained listed as microtektites.

TABLE 1. The number of >125 μm ODP Hole 689B microtektites recovered per gram dry sample.

mbsf*	tekt/g. sed.	125–200 μm	200–400 μm	400–600 μm
128.57	0.00	0	0	0
128.59	0.32	0	1	0
128.61	0.30	1	0	0
128.63	3.77	8	2	0
128.65	–	–	–	–
128.67	2.12	11	7	1
128.69	2.83	8	2	0
128.70	3.11	2	2	0
128.71	1.46	1	2	1
128.73	2.72	2	3	2
128.75	3.21	3	1	0
128.77	0.99	2	1	0
128.80	0.00	0	0	0

*Meters below seafloor
Microkrystites were found from 128.61 to 128.75 m below sea floor but were not counted per gram sample. The sample at 128.65 m below sea floor yielded microtektites but was not weighed properly.

A closer comparison of Maud Rise microtektites with North American strewn field tektites and microtektites shows some subtle chemical differences (Fig. 5a). Maud Rise microtektites are generally richer in Al_2O_3, and more depleted in MgO, CaO, and especially Na_2O for the same SiO_2 content. Furthermore, Maud Rise microtektites display considerable scatter in the FeO data and exhibit a wider range in SiO_2 content than North American strewn field tektites.

Maud Rise microkrystites chemically overlap Pacific microkrystites (Fig. 5b). They have a narrower range in SiO_2 content, which may be due to the fact that Pacific strewn field microkrystite data are compiled from studies at different sites.

Strontium Isotopic Composition of Hole 689b Microtektites and Popigai Melt Rock

A single $^{87}Sr/^{86}Sr$ analysis from a number of transparent Maud Rise spherules picked under the light microscope yielded a present day value of 0.7208. This is distinctly more radiogenic than published data for the North American strewn field tektites, ranging between 0.7120 and 0.7140 (Fig. 6, Table 2) (Ngo *et al.*, 1985; Shaw and Wasserburg, 1982; Stecher *et al.*, 1989). A number of larger tektites from DSDP Site 612 are exceptional (believed to belong to the North American strewn field (Koeberl, 1989; Stecher *et al.*, 1989)), which are more radiogenic and show substantial variation between individual tektites ($^{87}Sr/^{86}Sr$ values of 0.7330 to 0.7673)

We further analyzed a piece of melt rock (tagamite) from the ~100 km diameter Popigai crater in Siberia, kindly donated by S. Vishnevsky. The exact location of our sample within the crater is unknown. A $^{40}Ar/^{39}Ar$ age of 35.7 ± 0.2 Ma (Bottomley *et al.*, 1997) pinpoints this crater as a late Eocene impact. The Popigai tagamite sample has a present-day $^{87}Sr/^{86}Sr$ value of 0.7359 (Table 2). Based on a Sr and Rb content of 243 and 95 ppm, respectively (Vonhof, 1998), this relates to an initial $^{87}Sr/^{86}Sr$ ratio of 0.7357.

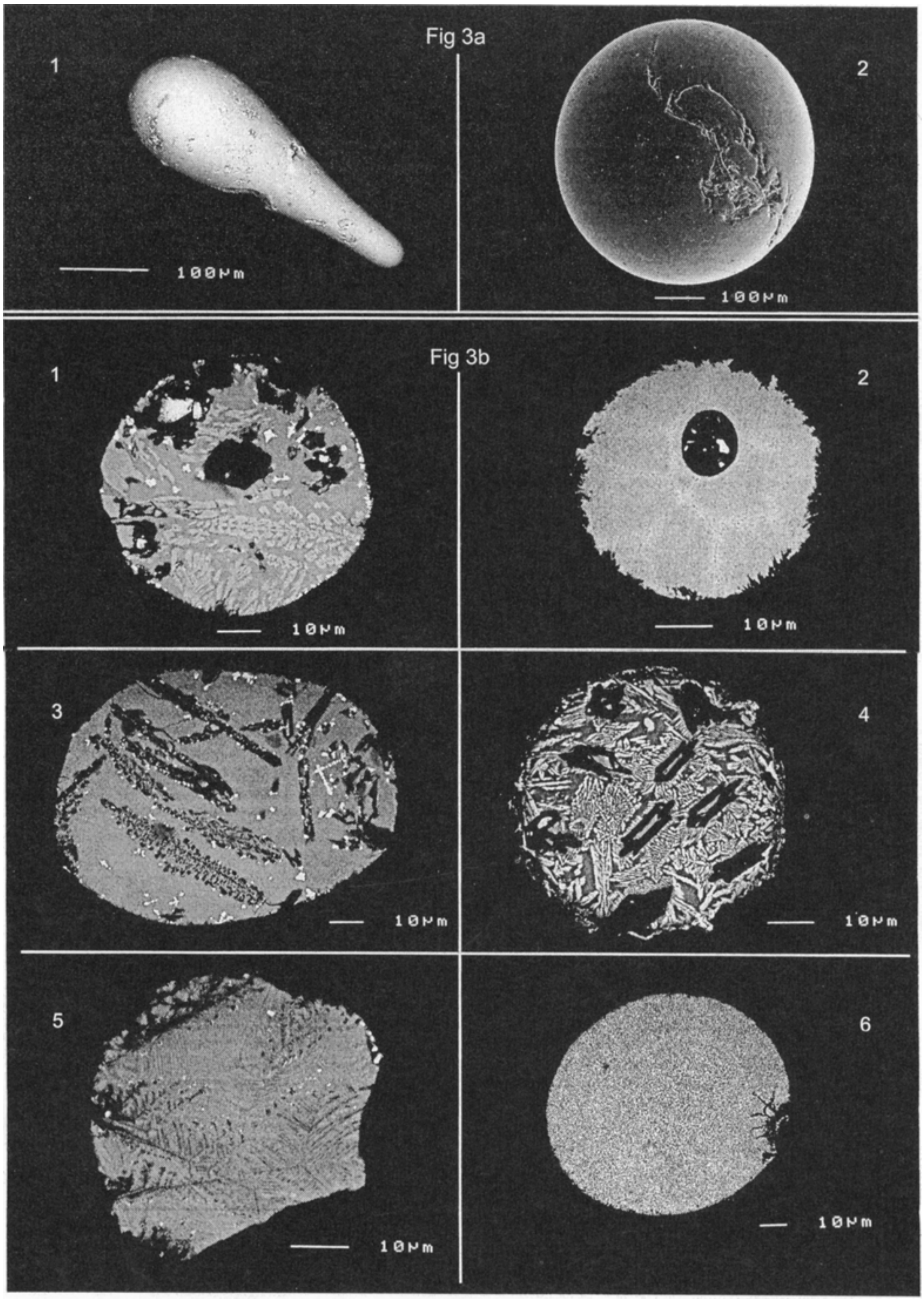

FIG. 3. (a) Scanning electron micrographs of Maud Rise microtektites. (1) Droplet-shaped microtektite testifies of its air-borne quenching. Dumbell-shaped specimens also occur. Note that star-shaped crystals on the tektite surface are an artifact; they precipitated during sample preparation. (2) One of the larger specimens with a conspicuous surface ornamentation. (b) Scanning electron micrographs of a thin section through Maud Rise microkrystites. (1) Specimen T(x) 4, showing elongated, light gray clinopyroxene crystals. Small bright white crystals are spinel. (2) "Kryptocrystalline" specimen T(z) 19 that looks like a tektite under the light microscope but shows to be finely crystallized under the SEM. Note that the (dark) bubble indicates crystallization of a liquid phase. (3) Microkrystite, T(y) 14, with dark coloured voids that were presumably occupied by clinopyroxene. Glass *et al.* (1985) refers to this type as "missing phase" microkrystites. (4) Microkrystite T(z) 36, with light coloured clinopyroxene crystals, and large elongated voids that we interprete to have been occupied by olivine crystals. (5) Microkrystite fragment T(z) 9, with partly "missing" and partly preserved clinopyroxene crystals. (6) Microkrystite T(z) 21 contains finely dispersed small crystals, presumably clinopyroxene and spinel. The micrograph shows a subtle concentric zonation in the density of these small crystals.

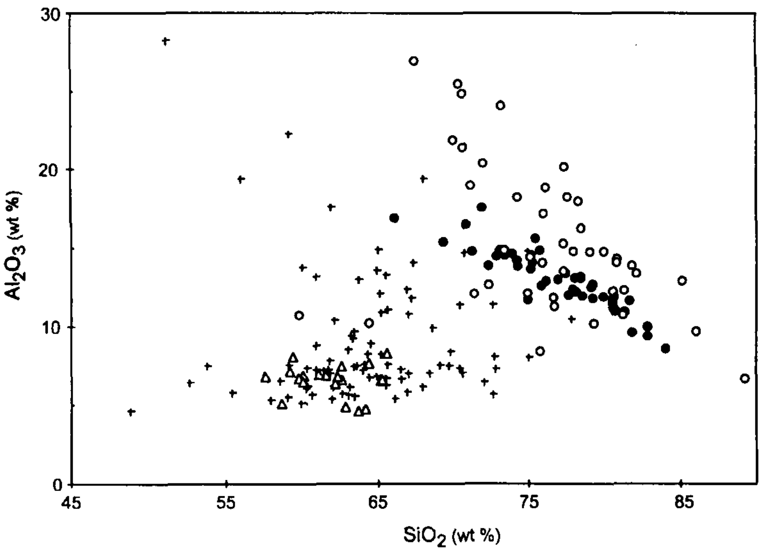

FIG. 4. Plot of SiO_2 and Al_2O_3 data (in wt%) from late Eocene impact spherules (data from Glass *et al.* (1985), Ngo *et al.* (1985), Shaw and Wasserburg (1982), Stecher *et al.* (1989), and this study). Explanation of symbols: (•) = North American strewn field tektites; (o) = Maud Rise microtektites; (+) = Pacific strewn field microkrystites; (Δ) = Maud Rise microkrystites. Maud Rise microkrystites occupy a relatively narrow range in the Pacific strewn field microkrystite field. Maud Rise microtektites have a more variable composition but partly overlap North American strewn field tektites.

Spinel and Microkrystite Formation

In the ejecta layer of the Massignano section, devitrified, spinel containing spherule "ghosts" were discovered by O. Pierrard and E. Robin (pers. comm., 1996). We have sampled this spherule layer and recovered abundant flattened spherules, part of which were greenish containing little spinel, and part were black and almost entirely composed of spinel crystals. Spinel occurs as octahedral and dendritic crystals, ranging in size from one to several tens of micrometers. Such spinel crystal habits are also found inside Maud Rise microkrystites, albeit the dendritic crystals appear smaller than in Massignano (Fig. 3b). Another conspicuous feature is the highly variable Cr content of the spinel crystals. Some of the small octahedral spinel of Maud Rise is in fact chromite (~40 wt% Cr_2O_3). Others, however, are magnetites, containing as little as 1–2 wt% Cr_2O_3 (Fig. 7, Table 3). Glass *et al.* (1985) also reported small octahedral chromite type spinel in Pacific strewn field microkrystites. Late Eocene spinel from a core in the central North Pacific (LL44-GPC3) contains ~1.5 wt% Cr_2O_3 (Robin *et al.*, 1995) and Massignano spinel averages ~5 wt% Cr_2O_3 (Pierrard *et al.*, 1998), with values up to 31 wt% for octahedral spinel.

Both types of spinel are Ni-rich (~2 wt%). Because Ni is rare in the Earth's crust but abundant in meteorite material, microkrystites are thought to be composed largely of meteoritic material. Gayraud *et al.* (1996) and Robin *et al.* (1992) proposed that these spinel-containing microkrystites originate as molten droplets ablated from meteorites traveling through the atmosphere.

DISCUSSION

Number of Strewn Fields

Although there is evidence for at least two impacts separated by 10–20 ka at sites in the Gulf of Mexico and the Caribbean (Glass *et al.*, 1985), from a stratigraphic point of view, both Massignano and Maud Rise may record a single late Eocene impact ejecta layer only. Because of the Ir anomaly and the presence of spinel bearing microkrystites in both sections, this single ejecta layer would most likely belong to the Pacific strewn field. However, a time gap of 10–20 ka would only represent some 7–15 cm in both sections. Considering low accumulation rates and small total numbers of microtektites per gram sediment for Maud Rise, as well as poor preservation of spherules in Massignano, it can not be excluded that bioturbation homogenized two originally separated strewn fields.

Maud Rise Microkrystites

Maud Rise microkrystites are in chemical composition and in appearance indistinguishable from those described for the Pacific strewn field. Further, strong similarities exist between the (chromite) spinel crystals in the Pacific strewn field and ODP 689B microkrystites. Although the Massignano and core LL44-GPC3 spinels have on average much lower Cr content, the considerable Cr variation for ODP 689B spinel suggests that the Cr/Fe ratio of spinel can vary substantially within a single strewn field. A similar conclusion was drawn by Kyte and Smit (1986) for spinels from the K-T boundary impact.

A number of studies show a single Ir anomaly in the late Eocene interval (Alvarez *et al.*, 1982; Ganapathy, 1982; Montanari *et al.*, 1993). The impact ejecta layers in Massignano and Maud Rise both have this Ir anomaly (Montanari *et al.*, 1993). At other sites where the Pacific strewn field and the North American strewn field are stratigraphically separated, an Ir anomaly correlates with Pacific strewn field microkrystites, and not with North American strewn field (micro)tektites (Glass *et al.*, 1985). These data are in accordance with a correlation of Massignano and Maud Rise impact ejecta layers to the Pacific strewn field. Such a correlation would enlarge the geographical extent of the Pacific strewnfield to (near) global proportions.

Maud Rise Microtektites

Microtektites of ODP Hole 689B are chemically slightly different from average North American strewn field (micro)tektites, especially in the Na_2O content. This may suggest a different origin of the Maud Rise microtektites, supported by their distinct $^{87}Sr/^{86}Sr$ ratio. The logical alternative would then be that Maud Rise microtektites belong to the Pacific strewn field. However, the chemical composition of the Pacific strewn field microtektites is quite similar to the glass of the associated microkrystites at the Caribbean/Pacific sites, whereas that of the Maud Rise microtektites clearly is not, with the exception of the two Mg-rich microtektites discussed above.

An important issue here is that not much is known, as yet, about the chemical homogeneity of the late Eocene strewn fields. Variable $^{87}Sr/^{86}Sr$ ratios of DSDP Site 612 tektites, interpreted to belong to the North American strewn field, show that cratering processes do not necessarily produce ejecta with homogenous $^{87}Sr/^{86}Sr$ compositions (Stecher *et al.*, 1989). Because DSDP Site 612 is interpreted to have been very close to the impact site (Koeberl, 1989; Stecher et al., 1989) it was suggested that especially proximal tektites are isotopically poorly mixed, or that they originate from yet another late Eocene impact on the North American continent (Stecher et al., 1989). Koeberl (1989) proposed that geochemical differences between North American strewn field

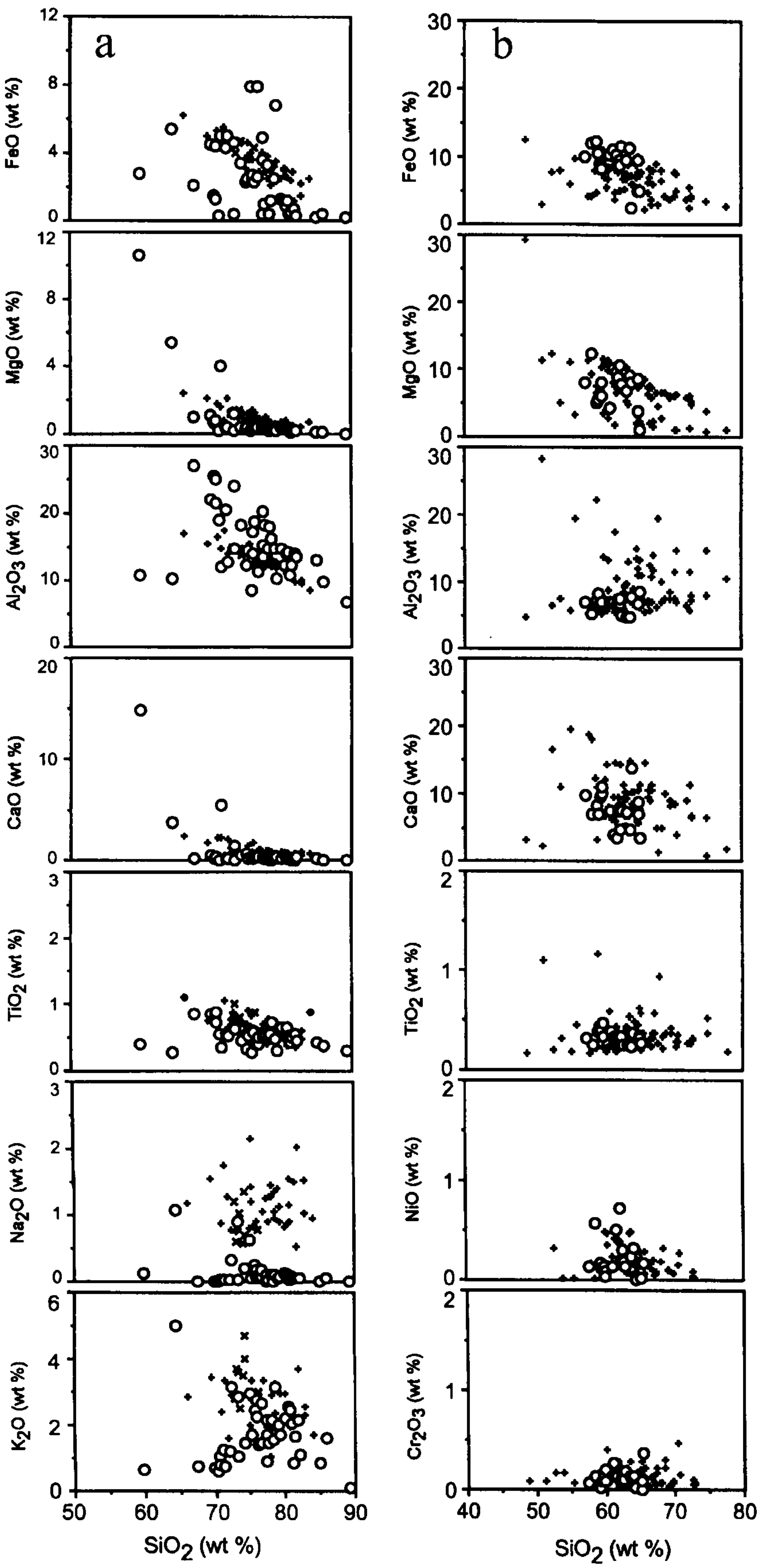

FIG. 5. (left) (a) chemical comparison of Maud Rise microtektites (o) with North American strewn field tektites (+), reported in wt%. For comparison, the somewhat anomalous North American strewn field tektites from DSDP Site 612 (Stecher *et al.*, 1989) are plotted with a separate symbol (×). Only in Na_2O does a distinct difference exist for North American strewn field tektites and Maud Rise microtektites. See text for further discussion. (b) Chemical comparison, reported in wt%, of Maud Rise microkrystites (o) with Pacific strewn field microkrystites (+), showing that they are indistinguishable. Data are taken from Glass *et al.* (1985), Ngo *et al.* (1985), Shaw and Wasserburg (1982), and Stecher *et al.* (1989).

tektites from different sites may reflect chemical mixing trends within a single strewn field, and suggested the chemically anomalous DSDP 612 tektites to reflect such a mixing trend within the North American strewn field. On the other hand, the narrow range in known $^{87}Sr/^{86}Sr$ ratios (0.0015) occupied by North American strewn field tektites when DSDP Site 612 is not taken in account (Ngo *et al.*, 1985; Shaw and Wasserburg, 1982; Stecher *et al.*, 1989) (Fig. 6), points towards an isotopically homogenous source for North American strewn field tektites. The $^{87}Sr/^{86}Sr$ data of tektites from other strewn fields show internal differences up to 0.0023 (Ivory Coast tektites), and 0.0055 (Australasian tektites) (Shaw and Wasserburg, 1982). The $^{87}Sr/^{86}Sr$ difference between Maud Rise microtektites and the most radiogenic North American strewn field tektites (DSDP Site 612 excluded) is 0.0072.

Ejecta deposits at Maud Rise, which we interpret as relatively distal from the impact site, may be chemically and isotopically different from more proximal ejecta, due to the heterogeneity of the impact target rock. Distal ejecta may represent the average composition of all target rocks better than the proximal tektites, which would be biased towards the composition of surficial target rock. If that is the case, in spite of their somewhat different chemical signature, the Maud Rise microtektites could well belong to the North American strewn field. Realising that it already is unusual that the two largest known impact events in the Cenozoic occur in such a short time interval, a third impact may seem unlikely.

On the other hand, a recent study of the isotopic composition of He in marine sediments of late Eocene age showed strongly increased input of interplanetary dust particles (IDP's) during a 2.5 Ma time interval spanning the late Eocene impacts. (Farley *et al*, 1998). Farley *et al.* (1998) tentatively interpret this increased IDP flux to relate to increased activity of long-period comets, leading to an increased chance of comet impacts on Earth. If this theory holds up, the likelihood of ODP 689B tektites belonging to a third large late Eocene impact would increase significantly.

The Chesapeake Bay and Popigai Impact Craters

The ~90 km diameter Chesapeake Bay structure near the North American east coast, has been

TABLE 2. Compilation of Sr concentrations and Sr-isotopic data from the present study and published data of tektites from four strewn fields.*

Sample	Sr ppm	$^{87}Sr/^{86}Sr$	Type
Stecher *et al.* (1989)			
DSDP 612-1	156	0.7256	NAS
DSDP 612-2	107	0.7246	NAS
DSDP 612-9	169	0.7257	NAS
DSDP 612-3	150	0.7306	NAS
DSDP 612-6	93	0.7473	NAS
DSDP 612-10	73	0.7487	NAS
DSDP 612-L1	85	0.7443	NAS
DSDP 612-L2	84	0.7446	NAS
B12	154	0.7123	NAS
B7-H	159	0.7126	NAS
B7-E	117	0.7136	NAS
B7-M	136	0.7177	Australasian
Shaw and Wasserburg (1982)			
B-229 (bediasite)	124	0.7136	NAS
B-306 (bediasite)	122	0.7131	NAS
B-312 (bediasite)	132	0.7128	NAS
2339 (georgiaite)	171	0.7133	NAS
6178 (georgiaite)	114	0.7126	NAS
Martha's Vineyard tektite	168	0.7132	NAS
Thai a	130	0.7189	Australasian
Thai b	128	0.7188	Australasian
Camb a	116	0.7186	Australasian
Camb b	111	0.7195	Australasian
Camb c	107	0.7191	Australasian
HiCaAus	291	0.7140	Australasian
HiMgAus	163	0.7163	Australasian
2051	159	0.7216	Moldavite
2233	130	0.7220	Moldavite
2226	136	0.7229	Moldavite
2052	124	0.7234	Moldavite
6011a	290	0.7233	Ivory coast
6011b	286	0.7236	Ivory coast
6011c	260	0.7257	Ivory coast
Ngo *et al.* (1985)			
Gays Cove C	145	0.7126	NAS
Bath Cliff D	142	0.7124	NAS
Bath Cliff tektites	149	0.7121	NAS
Vonhof and Smit (this study)			
av. ODP 689B tektites	139	0.7208	Maud Rise
Popigai Crater tagamite	243	0.7359	Popigai

The Sr concentration for the ODP 689B microtektites was kindly donated by C. Koeberl (pers. comm. 1998). The analytical uncertainty of Sr-isotopic analyses is typically better than 0.0001 (2 standard error values)
*North American strewn field (NAS) (micro)tektites (~35.5 Ma), Ivory Coast tektites (~1.1 Ma), Australasian tektites (~0.8 Ma), and Moldavites (~15 Ma).

suggested to be the possible source crater for the North American strewn field (Koeberl *et al.*, 1996). Its age, location, and chemical composition of the target rock compare well to the age, distribution, and composition of the North American strewn field tektites.

For the Pacific strewn field, the ~100 km diameter Popigai crater in Siberia is a possible source crater. At a $^{87}Sr/^{86}Sr$ ratio of 0.7359 for the Popigai impact melt, the Popigai ejecta should be distinct from the ~0.713 North American strewn field (Chesapeake Bay) tektites (provided the scattered $^{87}Sr/^{86}Sr$ ratios of the DSDP 612 tektites are not taken into account). The fact that the Maud Rise microtektites have a $^{87}Sr/^{86}Sr$ ratio of 0.7208 (a $^{87}Sr/^{86}Sr$ difference of 0.0151 compared to the Popigai tagamite sample, and 0.0073 compared to the North American strewn field tektites) does not favor either of the two craters at this point.

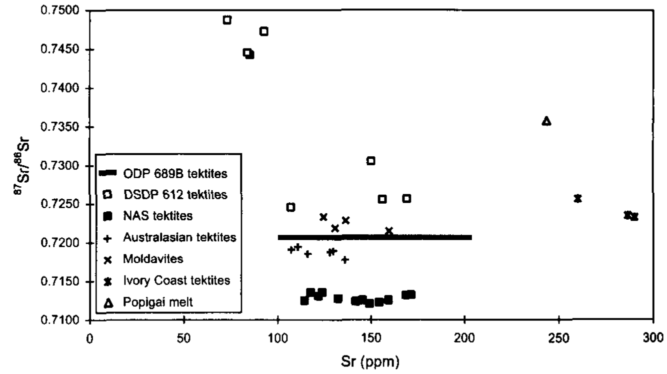

FIG. 6. A compilation of existing $^{87}Sr/^{86}Sr$ data for tektites from different impact events, the Maud Rise microtektite sample, and a piece of tagamite glass from the Popigai impact crater. Note the difference in $^{87}Sr/^{86}Sr$ between the North American strewn field tektites and the Maud Rise microtektites.

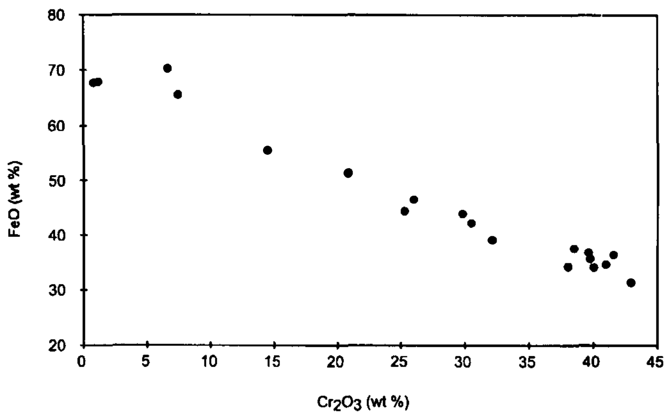

FIG. 7. Highly variable Fe and Cr content of spinel in Maud Rise microkrystites indicates that spinel Fe/Cr ratio may not be a suitable tool to distinguish between different strewn fields. A similar Fe/Cr variation has been observed between spinel crystals from different sites of the K-T boundary impact ejecta layer (Kyte and Smit, 1986).

CONCLUSIONS

Based on texture, chemical composition, and their association with an Ir anomaly, late Eocene microkrystites at 128.70 m below sea floor in ODP Hole 689B (Maud Rise, Southern Ocean) appear to belong to the Pacific strewn field. The occurrence of Pacific strewn field ejecta at this new high latitude location suggests that the Pacific strewn field is extended beyond the roughly equatorial distribution of previously reported occurrences (Fig. 1), and may even have had a global extension.

Microtektites from the same stratigraphic level in ODP Hole 689B differ only slightly in chemical composition from the North American strewn field tektites (see also Glass and Koeberl, 1999). However, the $^{87}Sr/^{86}Sr$ ratio of Maud Rise microtektites is ~0.0073 more radiogenic than average North American strewn field tektites. Because anomalous radiogenic North American strewn field tektites have previously been reported at DSDP Site 612, we favour the possibility that Maud Rise microtektites belong to a chemically heterogeneous North American strewn field. However, we can not exclude the possibility that the $^{87}Sr/^{86}Sr$ difference is distinctive, and that Maud Rise microtektites are the product of a third late Eocene impact event of the same age as the Pacific strewn field.

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TABLE 3. Microprobe data of 19 spinel crystals in five different Maud Rise microkrystites.*

Sample	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO	MgO	CaO	MnO	CoO	NiO	CuO	ZnO	Total
T(x)-02a	2.09	0.22	2.71	38.48	37.63	6.27	0.28	0.35	0.09	2.16	–	0.22	90.50
T(x)-02a	1.30	0.17	2.59	38.01	34.25	6.26	0.19	0.43	0.12	1.75	–	0.28	85.34
T(x)-02a	1.31	0.17	2.52	39.73	35.63	6.39	0.18	0.34	0.07	1.79	0.05	0.16	88.33
T(x)-02b	8.28	0.27	3.12	25.24	44.43	6.24	0.44	0.30	0.09	2.30	0.10	0.09	90.90
T(x)-02c	7.68	0.30	2.98	25.97	46.58	5.67	0.47	0.39	0.11	2.13	0.12	0.22	92.62
T(x)-02d	2.24	0.18	1.90	30.48	42.27	3.83	0.53	0.36	0.11	1.84	0.14	0.30	84.19
T(x)-02e	0.73	0.18	1.80	40.01	34.09	4.86	0.16	0.38	0.11	1.71	0.14	0.32	84.48
T(x)-01a	6.73	0.23	3.34	32.12	39.23	7.61	0.20	0.26	0.06	2.86	0.03	0.08	92.75
T(x)-01b	7.44	0.22	1.85	20.81	51.46	6.90	0.18	0.18	0.07	3.70	0.05	–	92.86
T(x)-01c	18.53	0.27	2.18	14.46	55.55	6.67	0.13	0.19	0.07	3.64	0.01	0.01	101.71
T(x)-04a	0.60	0.24	2.33	1.15	67.93	14.20	0.18	0.11	0.07	2.76	0.05	0.01	89.63
T(x)-04b	0.56	0.23	2.26	0.79	67.75	14.20	0.17	0.09	–	2.77	0.01	0.03	88.86
T(x)-04c	5.77	0.70	2.52	6.61	70.32	3.81	0.40	0.20	–	1.70	0.34	0.11	92.47
T(x)-04d	16.23	0.66	3.48	7.44	65.57	3.60	0.44	0.19	0.06	1.19	0.03	–	98.88
T(x)-12a	1.98	0.26	4.50	42.91	31.35	9.29	0.36	0.26	0.09	2.61	–	–	93.61
T(x)-12b	5.43	0.18	2.47	39.62	36.80	6.25	0.40	0.24	0.08	2.61	0.02	0.03	94.13
T(x)-12b	6.20	0.16	2.69	40.97	34.58	6.03	0.45	0.22	0.05	2.62	0.06	0.08	94.10
T(y)-14a	10.13	0.22	2.39	29.80	44.01	7.62	0.56	0.37	0.06	1.36	0.05	0.10	96.67
T(y)-14b	1.10	0.16	1.71	41.55	36.40	9.83	0.18	0.56	0.12	0.87	0.89	0.15	93.54

Note that higher SiO_2 wt% indicates contamination with matrix glass due to the very small size of the individual spinel crystals.All Fe is reported as FeO. The Fe_2O_3 was not calculated from stoichiometry because of this matrix contamination. As a result, totals can be somewhat low. Microkrystites T(x)-4 and T(y)-14 are also shown in Fig. 4.
*All data in wt%.

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